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Higgs Bosons in the Next-to-Minimal Supersymmetric Standard Model at the LHC

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Abstract

We review possible properties of Higgs bosons in the NMSSM, which allow to discriminate this model from the MSSM: masses of mostly Standard-Model-like Higgs bosons at or above 140 GeV, or enhanced branching fractions into two photons, or Higgs-to-Higgs decays. In the case of a Standard-Model-like Higgs boson above 140 GeV, it is necessarily accompagnied by a lighter state with a large gauge singlet component. Examples for such scenarios are presented. Available studies on Higgs-to-Higgs decays are discussed according to the various Higgs production modes, light Higgs masses and decay channels.

1 Introduction

One of the main goals of the Large Hadron Collider (LHC) is the detection of the Higgs boson, or of at least one of several Higgs bosons if corresponding extensions of the Standard Model (SM) are realized in nature. These searches depend crucially on the Higgs masses, production cross sections and the Higgs decays.

In the case of the SM, the production cross sections and decay branching ratios are quite well known as functions of the unknown Higgs mass [1]. In the Minimal Supersymmetric Standard Model (MSSM) with its extended Higgs sector and parameter space, these quantities have been studied as well and it seems that at least one of the Higgs bosons cannot be missed at the LHC [2–4] (we speak of a so-called no-lose theorem). There exist, however, well motivated scenarios with somewhat more extended Higgs sectors, as the Next-to-Minimal Supersymmetric Standard Model (NMSSM, see [5–7] for recent reviews), where the Higgs production rates and decays can differ strongly from both the SM and the MSSM. It is very important to be aware of the possibility of such unconventional properties of Higgs bosons; otherwise the absence of a signal in standard Higgs search channels, or unusual signals, may be completely misinterpreted.

Typical such unconventional properties of Higgs bosons in the NMSSM are Higgs-to-Higgs decays, Higgs boson with reduced couplings to gauge bosons, and/or Higgs masses incompatible with the MSSM. In the last years, many studies have been performed in order to investigate which scenarios are possible in the NMSSM, and by means of which signals they could be detected. Note that the interest in such studies is twofold: In some cases, it can be very challenging to detect a signal of any of the Higgs bosons of the NMSSM. In other cases a single signal is nearly as easy to see as in the MSSM, but only a detailed study of the complete visible Higgs spectrum can possibly allow to distinguish the NMSSM from the MSSM: For instance, the mass of the dominantly SM-like Higgs boson (with the largest couplings to electroweak gauge bosons) can be larger than 140 GeV in the NMSSM, with slightly reduced couplings to electroweak gauge bosons[1].

In the present paper we discuss the status of such NMSSM-specific Higgs properties and searches. We review the various possible scenarios, and the available studies on corresponding search strategies for Higgs bosons.

The Higgs sector of the NMSSM consists of two SU(2) doublets H_u and H_d (where, as in the MSSM, H_u couples to up-type quarks and H_d to down-type quarks and leptons), and one additional gauge singlet S. Due to its coupling $\lambda S H_u H_d$ in the superpotential, a vacuum expectation value (vev) s of S generates a supersymmetric mass term $\mu_{\text{eff}} = \lambda s$ for H_u and H_d. Since s and hence μ_{eff} are naturally of the order of the soft Susy breaking terms $\sim M_{\text{Susy}}$, this solves the so-called μ-problem of the MSSM [10]. Furthermore, in its simplest Z_3 invariant version, the superpotential of the NMSSM is scale invariant; it is in fact the simplest phenomenologically acceptable supersymmetric extension of the SM with this property. The NMSSM shares with the MSSM the unification of the running gauge coupling constants at a Grand Unification (GUT) scale, and the natural presence of a dark matter candidate in the form of a stable lightest supersymmetric particle (LSP).

[1]Such scenarios can be consistent with recent results reported by the CMS and ATLAS collaborations [8, 9].

The physical neutral Higgs sector in the NMSSM consists of 3 CP-even and 2 CP-odd states. (Here we do not consider the possibility of CP violation in the Higgs sector.) In general, these states are mixtures of the corresponding CP-even or CP-odd components of the weak eigenstates H_u, H_d and S, without the CP-odd Goldstone boson swallowed by the massive Z boson.

Many analyses of the Higgs sector of the NMSSM [11–26] pointed out that the physical eigenstates in the CP-even sector can well be strong mixtures of SU(2) doublet and singlet states with reduced couplings to gauge bosons. This motivated studies on the detectability of one or many Higgs states at LEP [15–19], the LHC [18, 20, 22–25] and a more energetic linear collider [14] (see also [27] for searches for Higgs bosons beyond the SM at linear colliders).

As mentioned first in [18], Higgs-to-Higgs decays can be important for Higgs detection in certain regions of the parameter space of the NMSSM. Notably the lightest CP-odd state A_1 can play the role of a pseudo-Goldstone boson [28, 29] whose small mass can lead to dominant $H \to A_1 A_1$ decays of CP-even states H [30–32]. The possibility of Higgs-to-Higgs decays inhibited to establish an all-embracing no-lose theorem for the NMSSM [22, 23], and triggered numerous studies on Higgs detection in such circumstances. The proposed strategies depend on the masses and branching ratios of the involved Higgs bosons, and will be reviewed in Chapter 4.

A list of benchmark points corresponding to unconventional scenarios in the Higgs sector of the NMSSM was proposed in [33], where the then available search strategies have been summarized. Non-standard Higgs boson decays were also reviewed in [34–36] and, in the light of the fine-tuning problem, in [37]. Both singlet-doublet mixings and Higgs-to-Higgs decays allow for SM-like CP-even Higgs bosons with masses well below 114 GeV, compatible with LEP constraints [38] alleviating the "little fine-tuning problem" of the MSSM [26, 30, 37, 39, 40]. The reduced Higgs couplings, Higgs production rates at the LHC and Higgs branching ratios in the NMSSM have recently been studied in [41].

In the next Chapter we briefly review the Higgs sector of the NMSSM, and present constraints. Chapter 3 is dedicated to NMSSM scenarios which allow to detect a Higgs boson in "standard" Higgs search channels. We focus on scenarios where signals can be visible, but where the properties of the Higgs states (masses above ~ 140 GeV, branching ratios or the number of distinct states) allow potentially to distinguish the NMSSM from the MSSM. These scenarios occur typically in the case of singlet/doublet mixings in the Higgs sector of the NMSSM. In Chapter 4 we consider scenarios which require dedicated search strategies, notably in the cases of dominant Higgs-to-Higgs decays. Conclusions are given in Chapter 5.

2 The Higgs sector of the NMSSM

The NMSSM differs from the MSSM due to the presence of the gauge singlet superfield S. In the simplest Z_3 invariant realisation of the NMSSM, the Higgs mass term $\mu H_u H_d$ in the superpotential W_{MSSM} of the MSSM is replaced by the coupling λ of S to H_u and H_d and a self-coupling κS^3. Hence, in this simplest version the superpotential W_{NMSSM} is scale

invariant, and given by:

$$W_{NMSSM} = \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 + \dots\ , \tag{1}$$

where hatted letters denote superfields, and the dots denote the MSSM-like Yukawa couplings of $\hat{H}_u$ and $\hat{H}_d$ to the quark and lepton superfields. Once the real scalar component of $\hat{S}$ develops a vev s, the first term in W_{NMSSM} generates an effective μ-term

$$\mu_{\rm eff} = \lambda s\ . \tag{2}$$

The phenomenological constraint $\mu_{\rm eff} \gtrsim 100$ GeV from the non-observation of charginos implies $s \gtrsim 100$ GeV$/\lambda$.

The soft Susy breaking terms consist of mass terms for the Higgs bosons H_u, H_d and S, and trilinear interactions (omitting squarks and sleptons)

$$-\mathcal{L}_{\rm Soft} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + \Big(\lambda A_\lambda\, H_u \cdot H_d\, S + \frac{1}{3} \kappa A_\kappa\, S^3 \Big) + \text{h.c.}\ . \tag{3}$$

Expressions for the mass matrices of the physical CP-even and CP-odd Higgs states – after H_u, H_d and S have assumed vevs v_u, v_d and s and including the dominant radiative corrections – can be found in [6] in will not be repeated here; below we just recall some relevant properties of the physical states. (We will use $\tan\beta = v_u/v_d$ and $v^2 = v_u^2 + v_d^2 \simeq (174\ \text{GeV})^2$.)

In the CP-even sector we find three states which are mixtures of the real components of H_u, H_d and S. The state h with the largest (often nearly SM-like) coupling to the electroweak gauge bosons has a mass squared M_h^2 given by[2]

$$M_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \text{rad. corrs.} + \Delta_{\rm mix}\ , \tag{4}$$

whereas the diagonal matrix element in the singlet sector is given by (assuming $s \gg v_u$, v_d)

$$M_{SS}^2 \simeq \kappa s (A_\kappa + 4\kappa s)\ . \tag{5}$$

The term $\Delta_{\rm mix}$ in (4) originates from singlet-doublet mixing and becomes for weak mixing

$$\Delta_{\rm mix} \simeq \frac{4\lambda^2 s^2 v^2 (\lambda - \kappa \sin 2\beta)^2}{\overline{M}_h^2 - M_{SS}^2} \tag{6}$$

where $\overline{M}_h^2$ is given by M_h^2 without the mixing term. Several remarks are in order.

First, neglecting singlet-doublet mixing, M_h can be larger than in the MSSM due to the second term in (4): up to ~ 140 GeV [42] if the running coupling λ is assumed to remain perturbative below the GUT scale, but up to ~ 300 GeV [43] if this assumption is given up.

Second, depending on the unknown parameters as A_κ and κs, M_{SS}^2 – and hence the mass of the singlet-like CP-even state – can be larger or smaller than $\overline{M}_h^2$. For $M_{SS}^2 > \overline{M}_h^2$

[2] We use h for the mostly SM-like CP-even Higgs boson, but H or H_i for general CP-even Higgs bosons.

we have $\Delta_{\rm mix} < 0$ in (4). Hence it is not guaranteed that the contribution to M_h^2 from the NMSSM specific terms in (4) – the sum of the second and forth terms on the right hand side – is positive. (Of course, the negative contribution from $\Delta_{\rm mix}$ vanishes if, accidentially, $\lambda \sim \kappa \sin 2\beta$.)

For $M_{SS}^2 < \overline{M}_h^2$, h is actually the second lightest Higgs state, and the mass of the singlet-like CP-even state is typically below 114 GeV. Now we have $\Delta_{\rm mix} > 0$ in (4), which can augment the mass M_h well above 140 GeV even for larger $\tan\beta$, where the second NMSSM specific term in (4) becomes small.

Now the mixing angle (i.e. the coupling to the Z boson) of the singlet-like CP-even Higgs state is constrained by LEP [38]: The non-observation of a signal at LEP leads to upper bounds on $\xi^2 \equiv \bar{g}^2 \times \overline{BR}(H \to b\bar{b})$ as function of M_H, where $\bar{g}$ is the reduced coupling of H to Z (normalized with respect to the SM), and $\overline{BR}(H \to b\bar{b})$ the branching ratio into $b\bar{b}$ normalized with respect to the SM. (The singlet-like CP-even state will still have $\overline{BR}(H \to b\bar{b}) \sim 1$.) For convenience we have reproduced the corresponding figure from [38] as Fig. 1 below.

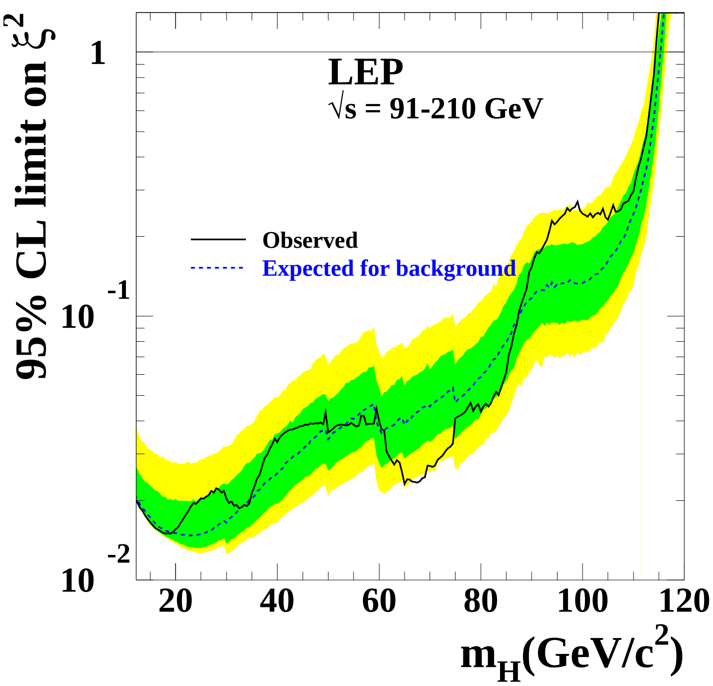

Figure 1: Upper bounds on $\xi^2 \equiv \bar{g}^2 \times \overline{BR}(H \to b\bar{b})$ from LEP [38]. Full line: observed limit; dashed line: expected limit; dark (green) shaded band: within 68% probability; light (yellow) band: within 95% probability.

One can note that, due to a slight excess of events, the upper bound on ξ^2 is particularly weak for M_H around $95 - 100$ GeV. This behaviour does certainly not require the presence of a Higgs state with a corresponding mass and $\xi^2 \sim 0.25$, but it could be explained by a

such a dominantly singlet-like CP-even Higgs state (not within the SM!).

Finally the singlet-like CP-even Higgs state can be lighter than $M_h/2$ such that the nearly SM-like Higgs h could decay dominantly into a pair of singlet-like CP-even Higgs states.

A third CP-even Higgs state has usually a mass close to the mass of one of the CP-odd (and the charged) Higgs states as in the MSSM. Defining $B_{\rm eff} = A_\lambda + \kappa s$, the CP-odd mass squared matrix has a diagonal element

$$M^2_{P,AA} = \frac{2\mu_{\rm eff} B_{\rm eff}}{\sin 2\beta} \; . \tag{7}$$

The diagonal element of the CP-odd mass squared matrix in the singlet sector is given by (assuming again $s \gg v_u,\, v_d$)

$$M^2_{P,SS} \simeq -3\kappa A_\kappa s \; . \tag{8}$$

Hence, depending on the unknown parameters, one can find a light CP-odd dominantly singlet-like state in the NMSSM. Considering the full CP-odd mass matrix, one obtains a massless physical Goldstone boson either in the Peccei-Quinn symmetry limit $\kappa \to 0$, or in the R-symmetry limit $A_\lambda,\ A_\kappa \to 0$ [28,29,44]. Hence a light CP-odd Higgs state A_1 playing the role of a pseudo-Goldstone boson is natural in the NMSSM, if any of these symmetries is approximately realized.

Phenomenological constraints on the mass M_{A_1} depend heavily on the coupling of A_1 to b-quarks. Normalized with respect to the corresponding coupling of the SM Higgs boson, the A_1-b-$\bar{b}$ coupling is

$$X_d = \tan\beta \cos\theta_A \tag{9}$$

where $\cos\theta_A$ denotes the SU(2) doublet component of A_1.

In any of the symmetry limits one has $\cos\theta_A \sim 1/\tan\beta$ leading to $X_d \sim v/s$ (Peccei-Quinn symmetry limit) or $X_d \sim 2v/s$ (R-symmetry limit) [6], hence typically to $X_d \ll 1$. On the other hand, if A_1 is coincidentally light outside a symmetry limit, $X_d > 1$ is possible as well.

For $M_{A_1} \lesssim 9$ GeV, upper bounds on X_d result from the non-observation of Υ decays into A_1 implying $X_d \lesssim 1$ [45, 46]. Constraints on M_{A_1}/X_d from B-physics are model dependend as they depend strongly on the flavour changing A_1-b-$\bar{s}$ vertex induced by loops of supersymmetric particles (sparticles) and on the charged Higgs mass [47].

For 9.2 GeV $\lesssim M_{A_1} \lesssim$ 10.5 GeV, $A_1 - \eta_b$ mixings become relevant [48, 49] with potentially desirable implications on η_b spectroscopy [50]. These allow to deduce (weaker) upper bounds on X_d from the non-observation of Υ decays [46] in this range of M_{A_1}, but also affect the A_1 decay channels which are now "inherited" to a large extend from the η_b decays into two gluons [51].

Clearly, for $M_{A_1} < M_h/2$, decays of the SM-like CP-even Higgs state h into $A_1\,A_1$ are relevant. The non-observation of such decays at LEP implies lower bounds on M_h depending on M_{A_1}:

For $M_{A_1} \gtrsim 10.5$ GeV, A_1 would decay dominantly into $b\bar{b}$. $h \to A_1 A_1 \to 4\,b$ decays have been searched for by the OPAL and DELPHI groups [52, 53] (summarized in [38]) leading to $M_h \gtrsim 110$ GeV for 10.5 GeV $\lesssim M_{A_1} \lesssim 55$ GeV.

For $M_{A_1} \lesssim 9.2$ GeV, A_1 would decay dominantly into $\tau^+\tau^-$ and is hardly affected by $A_1 - \eta_b$ mixings. The decay $h \to A_1 A_1 \to 4\,\tau$ has recently been re-analized by the ALEPH group [54] implying $M_h \gtrsim 107$ GeV if $\xi^2 \equiv \frac{\sigma(e^+e^- \to Zh)}{\sigma_{\rm SM}(e^+e^- \to Zh)} \times BR(h \to A_1 A_1) \times BR(A_1 \to \tau^+\tau^-)^2 \sim\ 1$, or $M_h \gtrsim 100$ GeV if $\xi^2 \sim\ 0.5$.

Due to the mostly gluonic decays of A_1 in the window 9.2 GeV $\lesssim M_{A_1} \lesssim$ 10.5 GeV [51], constraints on M_h for M_{A_1} in this window result mainly from the remaining (parameter dependend) branching ratio for the "standard" decay $h \to b\,\bar{b}$ [38], but not from limits on final states from $h \to A_1 A_1$.

Finally the charged Higgs boson mass is given by

$$M_{\pm}^2 = M_{P,AA}^2 + v^2\left(\frac{g_2^2}{2} - \lambda^2\right) \tag{10}$$

with $M_{P,AA}^2$ as in (7). Due to the last term $\sim \lambda^2$, the charged Higgs boson, compared to the corresponding CP-even and CP-odd Higgs bosons, can be somewhat lighter as in the MSSM. Lower bounds on $M_\pm$ result from the non-observation of charged Higgs bosons in top quark decays at the Tevatron [55, 56] and depend on $\tan\beta$. Stronger lower bounds on $M_\pm$ result from B-physics like $b \to s\,\gamma$, unless cancellations with sparticle-induced loop diagrams occur [47].

The full parameter space of the NMSSM includes also the decoupling limit $\lambda,\ \kappa \to 0$. Then the vev s becomes $s \sim M_{\rm Susy}/\kappa$, where $M_{\rm Susy}$ denotes the order of the soft Susy breaking terms. Hence we find $\mu_{\rm eff} \sim \lambda/\kappa \cdot M_{\rm Susy}$, and the μ-problem is still solved for $\lambda \sim \kappa$. In this limit the singlet-like CP-even and CP-odd Higgs states decouple and become unobservable, independent from their masses (which remain of $\mathcal{O}(M_{\rm Susy})$). Then the NMSSM could be distinguished from the MSSM only if the singlino-like neutralino is the LSP, appearing as final state in all sparticle decay cascades [57].

To summarize this Chapter, the following NMSSM specific scenarios are possible in the Higgs sector:

- CP-even Higgs bosons: Due to possibly large singlet-doublet mixing angles, more – potentially three! – CP-even states than in the MSSM could be observable, but with reduced signal rates for any of them. The dominantly SM-like state h can be heavier than in the MSSM. A dominantly singlet-like state with a mass below 110 GeV is compatible with LEP constraints, and can shift upwards (due to mixing) the mass of h beyond 140 GeV (see the next Chapter). A light dominantly singlet-like state can trigger dominant Higgs-to-Higgs decays of h.

- CP-odd Higgs bosons: The additional dominantly singlet-like state A_1 can again be quite light, triggering Higgs-to-Higgs decays $h \to A_1 A_1$. Depending on M_h and notably on M_{A_1}, many different cascade decays of h are possible, all of which require dedicated studies.

Before we review such studies in Chapter 4, we consider NMSSM specific phenomena in standard Higgs search channels in the next Chapter.

3 The NMSSM in Standard Higgs Search Channels

The establishment of a no-lose theorem in the absence of (dominant) Higgs-to-Higgs decays in the NMSSM [22, 24] relied essentially on the following Higgs production and decay channels at the LHC (where H denotes any of the three CP-even Higgs states; see also [58]):
– Vector Boson Fusion (VBF) with $H \to \tau^+\tau^-$;
– associate production of H with W or $t\bar{t}$, with $H \to \gamma\gamma$ and a charged lepton from W or $t\bar{t}$ in the final state;
– associate production of H with $t\bar{t}$, and $H \to b\bar{b}$.

Of course, many more channels contribute to SM-like Higgs searches, as gluon-gluon (gg) fusion and VBF with $H \to \gamma\gamma$, $H \to WW^{(*)}$, $H \to ZZ^{(*)}$ and various final states from $WW^{(*)}$, $ZZ^{(*)}$.

The most difficult scenarios in the NMSSM require up to 300 fb^{-1} integrated luminosity at the LHC for a clean signal. These correspond to cases where the mixing angles in the CP-even Higgs sector are large: The three physical Higgs states share their couplings to electroweak gauge bosons according to the sum rule

$$\sum_{i=1}^{3} \bar{g}_i^2 = 1 \; , \tag{11}$$

where $\bar{g}_i$ is the reduced coupling of H_i to $W^\pm$ or Z normalized with respect to the SM. In difficult scenarios, all $\bar{g}_i$ satisfy $\bar{g}_i^2 \lesssim 0.5$. Note that large mixing angles imply that the mass differences between the CP-even Higgs states are not large, hence one finds typically $m_{H_i} \lesssim 200$ GeV, $i = 1, 2, 3$, in such scenarios. (Similar observations have been made in case studies in [33, 59, 60].)

On the other hand, precisely such scenarios allow potentially for the simultaneous observation of several Higgs states in the NMSSM, with masses and couplings incompatible with the MSSM. Corresponding studies of signal rates for $H_i \to \gamma\gamma$ (production cross sections times branching ratios) have been performed in [25]. More complete studies (including more relevant Higgs production and decay channels) concerning the question under which circumstances the simultaneous observation of several Higgs states would allow to distinguish the NMSSM from the MSSM would certainly be challenging, but highly welcome.

In the case of Higgs decays into two photons, already the observation of a single state can give us possibly a hint in this direction: If the SM-like and singlet-like states are strongly mixed, the coupling of the lighter eigenstate to b-quarks can be strongly suppressed, implying a strong reduction of the corresponding partial width into $b\bar{b}$ and a corresponding enhanced branching ratio into $\gamma\gamma$ [61, 62]. Inspite the somewhat reduced Higgs production rate, the signal rate for this process can be six times larger than in the SM or in the MSSM – and this for a Higgs mass possibly well below 114 GeV, but still compatible with LEP constraints due to the reduced Higgs coupling to the Z boson.

Another feature allowing to distinguish the NMSSM from the MSSM could be the mass of the mostly SM-like Higgs boson h. If this state is the lightest among all NMSSM CP-even Higgs bosons, the upper bound on its mass is about ~ 140 GeV [42] for $\lambda \sim 0.7$ (at the boundary of validity of perturbation theory below the GUT scale), low $\tan\beta$ and κ such that the negative term Δ_{mix} in (4) is small. However, the mostly SM-like Higgs boson can

λ	0.70	0.70	0.71
κ	0.20	0.16	0.23
$\tan\beta$	2.73	2.70	2.65
A_λ	915 GeV	928 GeV	895 GeV
A_κ	-340 GeV	-230 GeV	-330 GeV
μ_{eff}	320 GeV	310 GeV	330 GeV
M_{H_2}	140 GeV	145 GeV	150 GeV
ξ_2	0.92	0.86	0.73
$BR(H_2 \to WW)$	0.54	0.64	0.75
$BR(H_2 \to ZZ)$	0.071	0.082	0.087
$BR(H_2 \to bb)$	0.29	0.20	0.11
$BR(H_2 \to \tau\tau)$	0.031	0.022	0.011
$BR(H_2 \to \gamma\gamma)$	2.3×10^{-3}	2.1×10^{-3}	1.7×10^{-3}
$BR(H_2 \to Z\gamma)$	2.8×10^{-3}	2.9×10^{-3}	2.6×10^{-3}
$BR(H_2 \to gg, cc)$	0.063	0.052	0.037
M_{H_1}	91 GeV	97 GeV	115 GeV
ξ_1	0.40	0.51	0.68

Table 1: Three examples of scenarios where the state H_2 corresponds to the most SM-like Higgs boson h with a mass $\geq$ 140 GeV. We show its reduced couplings ξ_2 to electroweak gauge bosons, its branching fractions, the mass M_{H_1} of the lighter more singlet-like state as well as its reduced coupling ξ_1.

well be the next-to-lightest CP-even state H_2 in the NMSSM (see Chapter 2), in which case its mass can be larger [21] due to a positive term Δ_{mix} in (4). Then its reduced coupling $\xi \equiv \bar{g}$ to electroweak gauge bosons is necessarily smaller than 1, in fact ξ decreases with increasing M_{H_2}.

In Table 1 we show three examples of this behaviour, corresponding to $M_h \equiv M_{H_2} =$ 140 GeV, 145 GeV and 150 GeV[3]: ξ_2 decreases from 0.92 to 0.73; the lighter state H_1 has $\xi_1 < \xi_2$ allowing it to escape LEP constraints inspite of its mass down to 91 GeV. Note that $\xi_1^2 + \xi_2^2 \sim 1$; the third CP-even Higgs boson with a mass of about 950 GeV has $\xi_3 \sim 0$ for the points shown in Table 1. The value $\xi_1 = 0.51$ for $M_{H_1} \sim 97$ GeV seems large at first sight; however, precisely for this mass range the LEP bounds are particularly weak [38] and allow for $\xi^2 \sim 0.25$. For completeness we also show in Table 1 the branching ratios of the more visible state H_2. The state H_1 would be extremely difficult to observe at the LHC as it decays nearly exclusively into $b\bar{b}$; its branching ratios into $\gamma\gamma$ are $\lesssim 1 \times 10^{-3}$, and into $\tau^+\tau^-$ about 0.09.

To conclude, various NMSSM-specific signals are possible in standard Higgs search channels at the LHC: signals in the $W^+W^-/ZZ/\gamma\gamma/b\bar{b}$ final state for Higgs masses $\geq$ 140 GeV

[3] These results have been obtained with the help of the code NMHDECAY inside NMSSMTOOLS [63,64], including the full 1-loop and full α_s/h_{top} two-loop corrections as in [65]. The soft Susy breaking parameters not shown in Table 1 are 1.2 TeV for the gluino mass, 1.5 TeV for all squark masses, $A_{top} = -3$ TeV and $m_{top} = 173.1$ GeV.

(incompatible with the MSSM); more visible states than in the MSSM (although corresponding studies should be extended) and exceptionally large signal rates in the $\gamma\gamma$ final state, possibly for unexpectedly small Higgs masses.

4 Searches for Higgs-to-Higgs Decays

We have seen in Chapter 2 that many different final states are possible in the presence of Higgs-to-Higgs decays. Concentrating on $h \to A_1 A_1$, A_1 would decay dominantly into $b\bar{b}$ for $M_{A_1} \gtrsim 10.5$ GeV, into gg for 10.5 GeV $\gtrsim M_{A_1} \gtrsim 9.2$ GeV, into $\tau^+\tau^-$ for 9.2 GeV $\gtrsim M_{A_1} \gtrsim 3.5$ GeV, and into $\mu^+\mu^-$ for $M_{A_1} \lesssim 3.5$ GeV. However, subdominant A_1 decays can often lead to more promising signals. With the exception of gluonic decays due to $A_1 - \eta_b$ mixing, the subsequent discussion also covers light CP-even states H_1 and $h \to H_1 H_1$ decays (if $h \equiv H_2$). In the present Chapter we review existing studies on Higgs-to-Higgs decays for the LHC. (An overview over possible reduced couplings of Higgs bosons, Higgs production cross sections and branching ratios in various channels and various regions in the parameter space of the NMSSM is given in [41].)

The first attempt for $M_{A_1} \gtrsim 10.5$ GeV was made in [23] concentrating on h production via Vector Boson Fusion, where forward and backward jet tagging can be exploited. Not enforcing b-tagging, the QCD background to the $4b$ final state would be overwhelming (as for h production via gluon fusion [66]); hence, the subdominant final state $2b + 2\tau$ was considered. Assuming a value for M_{A_1}, two central jets with $M_{jj} \sim M_{A_1}$ were required. From the two leptons with the highest transverse momentum and p_T^{miss} an invariant mass $M_{\tau\tau}$ was deduced, and finally the invariant mass $M_{jj\tau\tau}$ was plotted. A large background comes from $t\bar{t}$ production. For $L = 300$ fb^{-1}, sizeable ratios $S/\sqrt{B}$ were obtained depending, however, on the accuracy with which the background shape could be predicted. Moreover, an analysis including detector simulation and, notably, more realistic lepton identification efficiency lead to much less optimistic results [67].

Subsequently it was pointed out in [68] that Higgs-Strahlung off W bosons (and, more marginally, off $t\bar{t}$ pairs) can help to establish a signal for $h \to A_1 A_1$ decays, since one can trigger on an isolated lepton (with, e.g., $p_T \gtrsim 20$ GeV) from leptonic W decays. However, only a preliminary analysis of production cross sections times branching ratios – without cuts and background studies – was performed in [68].

More detailed studies of Higgs-Strahlung off W bosons including backgrounds, cuts and simulations were performed in [69, 70]. In contrast to [23], b-tagging efficiencies of 0.7 were assumed in [69], and of 0.5 (for $E_T^{jet} > 15$ GeV) in [70]. This allows to consider the $4b$ final state from $h \to A_1 A_1 \to 4b$ (and the $2b + 2\tau$ final state [70]). Plotting the invariant mass M_{4b}, sizeable significances $S/\sqrt{B} > 5$ for an integrated luminosity $L = 30$ fb^{-1} were found for benchmark points from [33] with $M_h \sim 110$ GeV and $M_{A_1} \sim 30 - 40$ GeV in [69], and for $M_{A_1} \sim (M_h - 10\,\text{GeV})/2$ in [70]. Of course, the assumed b-tagging efficiencies and mistag probabilities are crucial for these results; hence, corresponding studies including detector acceptances would be welcome.

In some particular cases, other final states could allow to detect Higgs-to-Higgs decays: If the branching ratio for $A_1 \to \gamma\gamma$ is enhanced ($BR(h \to A_1 A_1 \to 4\gamma) \gtrsim 10^{-4}$), the 4γ final state can be visible [71]. If λ is very large ($\lambda \sim 2$ in λSusy [72]), $h \equiv H_1$ with

a mass $M_h \sim 250$ GeV will decay dominantly into electroweak gauge bosons leading to interesting signals in $H_2 \to 2h \to 4(Z \text{ or } W)$ or $A_2 \to Zh \to ZZZ$ or ZWW, where $M_{H_2} \sim M_{A_2} \gtrsim 500$ GeV [72].

The 4τ final state will be relevant for small A_1 masses. In [73], both Higgs-Strahlung and VBF h production processes were considered, and the $2\,\mu + 2\,j + E_T^{miss}$ final state from 4 τ-leptons was exploited. After simulation of the processes, selection cuts were applied and signal cross sections (after selection cuts) were given for a range of parameters corresponding to $M_{A_1} < 10$ GeV, M_h from 20 to 130 GeV (respecting LEP constraints [38] before the ALEPH analysis [54]). Notably for $M_h \gtrsim 100$ GeV (hardly affected by ALEPH constraints [54]), signal cross sections up to 10 fb (Higgs-Strahlung) and 80 fb (VBF) were found. However, backgrounds and detector performances have not been included in this study.

An extensive study on searches for $h \to A_1 A_1 \to 4\tau$, including all h production processes, background processes and the performances of the ATLAS detector, was performed in [74]. For M_h from 100–130 GeV and 5 GeV $< M_{A_1} <$ 10 GeV, a signal significance of ~ 5 was obtained for $L = 30$ fb^{-1} in the $4\mu + E_T^{miss}$ final state from $h \to A_1 A_1 \to 4\tau \to 4\mu +$ neutrinos in h production via VBF.

The subdominant decay channel $h \to A_1 A_1 \to 2\mu + 2\tau + E_T^{miss}$ (with h from gluon fusion) was analysed in [75]. Inspite of the reduction of the signal rate by the factor $(m_\mu/m_\tau)^2$, it was argued that the clean signal in the dimuon invariant mass allows to cover most of the relevant region of the parameter space already with $L \sim 5$ fb^{-1} at the LHC. (However, the magnitude of the QCD multijet background estimated in [75] was found to be three orders of magnitude larger in [76].)

Another possibility for the study of $h \to A_1 A_1 \to 4\tau$ is the central exclusive production (CEP) of h, $pp \to p + h + p$ [77]. This requires the installation of forward proton detectors in the high dispersion region as in the FP420 project [78]. According to the results of simulations of the signal and backgrounds including pile up in [77], a significant signal can be obtained for sufficient instantaneous and integrated luninosity.

If $M_{A_1} < 2\,m_\tau$, the process $h \to A_1 A_1 \to 4\mu$ is very promising. Analyses of the h production cross sections (via gluon fusion and associate production with $b\bar{b}$) times branching fractions have been performed in [76], and were compared to the QCD multijet background. Requiring at least one μ with $p_T > 20$ GeV (4 muons with $p_T > 5$ GeV) and plotting invariant masses of opposite charge dimuon pairs as well as the $M_{4\mu}$ invariant mass, most of the parameter space corresponding to $M_{A_1} < 2\,m_\tau$ allows for the detection of both A_1 and h already for $L \sim 1$ fb^{-1} at the LHC [76].

In the case of large $\tan\beta$, the associate production of h with b-quarks is interesting. In [79], signal rates for $pp \to b\bar{b}h \to b\bar{b}A_1 A_1$ (and $pp \to b\bar{b}h_2 \to b\bar{b}h_1 h_1$) times branching fractions into 4γ, $4b$, $2b\,2\tau$, 4τ and 4μ final states (in addition to the prompt b-quark pair) are given, but more dedicated analyses are required in these cases.

Another potentially interesting Higgs-to-Higgs decay process is the decay of a charged Higgs boson $H^\pm$ into $W^\pm + A_1$ (or $W^\pm + h$ [80]). Branching ratios for $H^\pm \to W^\pm + A_1/h$ and cross sections for the processes $pp \to H^\pm A_1 \to W^\pm A_1 A_1$ (and $pp \to W^\pm h \to W^\pm A_1 A_1$, which can be of similar order) are given in [81], the branching ratios for $H^\pm \to W^\pm + A_1$ have also been studied in [41, 60].

A light NMSSM specific CP-odd Higgs boson A_1 might also be visible in direct production channels, without relying on $h \to A_1 A_1$ decays. For $M_{A_1} \lesssim 12$ GeV, the (subdominant) decay $A_1 \to \mu^+\mu^-$ can allow for A_1 detection via gluon-gluon fusion [82] due to the clean signal (for sufficiently large $\tan\beta$, such that the b-quark-loop induced production rate is sufficiently large in spite of the dominantly singlet-like nature of A_1). First searches by ATLAS based on 35.4 pb^{-1} integrated luminosity did not discover a signal [83], but with more accumulated data the prospects will be more promising.

At large $\tan\beta$, the associate production of A_1 with a $b\bar{b}$ pair can become relevant for M_{A_1} up to M_Z [84–86]. The two-photon and $\tau^+\tau^-$ decay modes of A_1 have been analysed in [84], where appropriate cuts have been applied and signal-to-backbround ratios been studied for 300 fb^{-1} integrated luminosity at the LHC. The two-photon decay mode of A_1 seems too small, but the $\tau^+\tau^-$ decay mode can lead to a sufficiently large signal-to-backbround ratio. The subdominant $\mu^+\mu^-$ decay mode of A_1 has been analysed in [85]. It can lead to a signal for 30 fb^{-1} integrated luminosity if M_{A_1} is in the range $10 - 40$ GeV, whereas more integrated luminosity would be required for larger values of M_{A_1}. In the $4b$ final state and with high b-tagging efficiency, a signal may be visible for M_{A_1} in the range $20 - 80$ GeV [86].

Light Higgs bosons of the NMSSM could also be produced in sparticle decay cascades. Branching fractions for neutralino decays into neutralinos plus A_1 have been studied in [87, 88], and for sbottom/stau decays into sbottom/stau plus A_1 in [89]. Simulations of such processes have not been performed, with the exception of gluonic decays of A_1 (see below) in [90].

Clearly a dominant A_1 decay into two gluons, and hence a dominant h decay into $h \to A_1 A_1 \to 4g$, would constitute a major challenge for h detection at the LHC. As discussed in Chapter 2 this would happen for 9.2 GeV $\lesssim M_{A_1} \lesssim$ 10.5 GeV, in which case the search modes discussed above would fail. Recently it has been proposed that the analysis of jet substructures could come to the rescue in such situations [90–93].

Here one concentrates on h production in association with a W boson, where an isolated lepton from the W decay helps to trigger on the events [91–93]. (h production in sparticle decay cascades has been considered in this context in [90].) In addition one requires two jets with large p_T, which originate from decays $h \to A_1 A_1 \to 2j$ with boosted A_1 bosons. Decays of boosted Higgs bosons allow to search for jet substructures [94, 95]. Here one assumes that the decay $A_1 \to 2g$ gives rise to a single "fat" jet j, whose substructure can be analysed: undoing the last recombination step of the clustering algorithm which generated the jet j leads to the decomposition $j \to \{j_1, j_2\}$. Typically one requires $m_{j_1} \sim m_{j_2} \ll m_j \lesssim 12$ GeV, and not more jets with large p_T than required for a signal. Plotting m_{jj} of the events satisfying corresponding criteria [90–93] can lead to visible peaks for $m_{jj} \sim m_h$.

Analyses based on jet substructure are not confined to dominant gluonic decays of A_1; they can also be applied to larger A_1 masses leading to dominant $A_1 \to b\bar{b}$ decays [93] and, notably, to $A_1 \to 2\tau$ decays [96] where two hadronically decaying τ leptons from a boosted A_1 form a single "fat" ditau jet.

For convenience we have summarized the available studies of Higgs-to-Higgs decays and single A_1 production processes at the LHC, for different ranges of M_{A_1} and ordered

M_{A_1}:	$\gtrsim 10.5$ GeV				$\lesssim 10.5$ GeV		$< 2\,m_\tau$
	$h \to A_1\,A_1$						
Final state:	$4b$	$2b + 2\tau$		4γ	4τ	$2\tau + 2\mu$	4μ
h production mode:							
VBF:		[23]*, [67]**			[73]*, [74]**		
$W/Z + h$:	[69]*, [70]*	[68]			[73]*, [96]*		
gg:				[71]*		[75]*	[76]*
CEP:					[77]**		
$b\bar{b}h$:	[79]	[79]		[79]	[79]		[76]*
	Single A_1 production						
Final state:	$2b$	2τ	2μ	2γ	2τ	2μ	2μ
A_1 production mode:							
gg:						[82]*	
$b\bar{b}A_1$:	[86]*	[84]*	[85]*	[84]*	[84]*	[85]*	[85]*
$H^\pm \to W^\pm A_1$	[81]				[81]		

Table 2: Available studies of Higgs-to-Higgs decays and single A_1 production at the LHC, for different ranges of M_{A_1}. (CEP stands for central exclusive production.) []* indicates that, apart from signal rates, signal and background processes have been simulated or estimated. []** indicates that, in addition, the detector response has been included in the study. (The gluon-gluon final state, relevant for M_{A_1} in the range $M_{A_1} \sim 10 \pm 0.5$ GeV, has been left aside.)

according to production processes and final states, in Table 2. Some of these studies are confined to estimates of production cross sections times branching fractions. Studies including simulations of background processes and estimates of signal to background ratios after cuts are indicated by an asterisk; two asterisks indicate studies including detector simulations. (The gluonic decay $A_1 \to gg$ is left aside in Table 2.)

It should also be noted that in many cases specific ranges of parameters are required, such that the production cross sections and/or branching fractions are large enough allowing for sufficiently significant signals. Hence the existence of a study of a given channel implies by no means that a discovery of the corresponding process (for corresponding Higgs masses) is guaranteed; moreover, simulations including the detector response are missing in most cases.

5 Conclusions

In various regions of the parameter space of the NMSSM, the properties of Higgs bosons are clearly distinct from the MSSM: A completely SM-like Higgs boson can have a mass up to 140 GeV, and a dominantly SM-like Higgs boson (with somewhat reduced couplings to

electroweak gauge bosons) can be heavier. In this case this Higgs boson has a non-vanishing singlet component, and is necessarily accompagnied by a lighter state which is equally a doublet-singlet admixture with a mass and couplings typically allowed by LEP constraints.

In other regions of the parameter space, branching ratios into two photons can be enhanced due to a strong suppression of the partial width into $b\bar{b}$.

In spite of numerous studies of Higgs-to-Higgs decays, a no-lose theorem could not be established up to now. For $M_{A_1} \gtrsim 10.5$ GeV, the most promising studies in [69, 70] on the $4b$ final state must be confirmed with respect to the assumed b-tagging efficiencies, mistaggings and backgrounds by studies including detector simulations. The latter are also required for the analyses of the gluonic decays for M_{A_1} around 10 GeV in [90–93], where the study of jet substructures requires measurements of invariant masses of very slim (but very boosted) jets. For $M_{A_1} \lesssim 9.2$ GeV and dominant $h \to A_1 A_1 \to 4\tau$ decays, the studies in [74, 77] seem promising, whereas the QCD background assumed in the analysis of the $2\tau 2\mu$ final state in [75] needs to be confirmed. Background and detector simulations are also required for the proposals for direct A_1 production in [82,84–86], where the significance of the signal rates depend on model parameters as $\tan\beta$. Hence, further studies on Higgs-to-Higgs decays are still necessary, if one wants to be sure that at least one Higgs boson of the NMSSM is visible at the LHC.

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